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Modeling aquifer behaviour under climate change and high consumption: Case study of the Sfax region, southeast Tunisia

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ABSTRACT

The water resources are exhausted by the increasing demand related to the population growth. They are also affected by climate circumstances, especially in arid and semi-arid regions. These areas are already undergoing noticeable shortages and low annual precipitation rate. This paper presents a numerical model of the Sfax shallow aquifer system that was developed by coupling the geographical information system tool ArcGIS 9.3 and ground water modeling system GMS6.5's interface, ground water flow modeling MODFLOW 2000. Being in coastal city and having an arid climate with high consumption rates, this aquifer is undergoing a hydraulic stress situation. Therefore, the groundwater piezometric variations were calibrated for the period 2003–2013 and simulated based on two scenarios; first the constant and growing consumption and second the rainfall forecast as a result of climate change scenario released by the Tunisian Ministry of Agriculture and Water Resources and the German International Cooperation Agency "GIZ" using HadCM3 as a general circulation model. The piezometric simulations globally forecast a decrease that is about 0.5 m in 2020 and 1 m in 2050 locally the decrease is more pronounced in "Chaffar" and "Djbeniana" regions and that is more evident for the increasing consumption scenario. The two scenarios announce a quantitative degradation of the groundwater by the year 2050 with an alarming marine intrusion in "Djbeniana" region.

1. Introduction

The water resources are considered as the most important elements in the regions with low rainfall and high evapotranspiration (Tweed et al., 2011). In fact, according to Hetzel et al. (2008), the decreasing trend of water table levels in several aquifers is mainly due to overexploitation, which leads to the salinization of the coastal groundwater. The water resources importance is particularly highlighted in areas where aquifers are overexploited for urban, agricultural and industrial activities. Actually the current water use in Tunisia is distributed as the following; 80% for agriculture, 11% for individuals and communities, 7% for industry and about 1% for tourism (MARH, 2006). Therefore, the rate of shallow groundwater consumption is increasing continuously from 103% in 1995 to 114% in 2011, while that of deep groundwater has increased from 77% to 94% for the same years (MEATDD and ANPE, 2014). There exist some other factors that may threat the availability of groundwater, such as the sea water intrusion, resulting a negative variation in the quantity and quality of water in the aquifer by the phenomenon of salinization (Trabelsi et al., 2005; Cobaner et al., 2012; Masciopinto, 2013) in addition to the climate change phenomenon (Woldeamlak et al., 2007; Zarhloule et al., 2009; Piao et al., 2010; Boughariou et al., 2014; Kumar 2014). The climate change causes an intensification of the hydrological cycle (Irish et al., 2010), which is manifested by an increase in precipitation in the rainy zones and a decrease in the arid zones and Drain like the Mediterranean basin (Niasse 2005; In Laube et al., 2012; Spohr, 2011). According to Plan Bleu (2008), the Mediterranean zones that are the most vulnerable to the reduction of their water resources are those of North Africa close to the desert zones, the large deltas, the coastal zones as well as the areas of high population growth and that are socially vulnerable (The Mediterranean shores to the South and East). In this context several studies highlight the global warming impact on Mediterranean water resources (Iglesias et al.,

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2007; Santos et al., 2014).

Barron et al., 2010 found that the rainfall is the most important parameter affecting recharge and that rainfall intensity and temperature also cause significant variations in recharge. Hence, the rivers, groundwater and snowmelt regions will suffer from a decrease in the level of water in arid and semi-arid areas with low precipitation. The studies on the impact of climate change focus on the surface water rather than groundwater due to the fact that the aquifer reservoirs are concealed, and the measurements of their fluctuations are less obvious than those that do not facilitate the prediction of their behavior under the effect of climate change (Lenart, 2006). Accordingly, simulating the behavior of aquifers under the effect of climatic variations attracts the interest of the decision makers and the researchers. The latter seek to understand well the global and regional manifestations of the climatic changes and try to use the numerical modeling as tool. The study of the impact of climate change on groundwater resources requires either reliable forecasting of changes in the major climatic variables or accurate estimation of groundwater recharge. Based on different scenarios, the studies have been conducted to forecast fresh water evolution (Parkin et al., 1996; Von Gunten et al., 2015; Ertürk et al., 2014; Molina- Navarro et al., 2014; Sellami et al., 2016; Viola et al., 2016) and water table behavior (Jackson et al., 2011; Goderniaux et al., 2011; Stigter et al., 2014; Piras et al., 2014; Hartmann et al., 2014; Bougharious et al., 2014; Lemieux et al., 2015; Goderniaux et al., 2015; Caballero and Ladouche, 2015; Hartmann et al., 2015; Duran-Encalada et al., 2017). The studies of groundwater spatio-temporal evolution are taking into consideration two major factors which are abstraction and recharge. These factors will be linked to the climate variation. Most of the studies follow a general approach to project the impact of climate change on groundwater resources (Brouyère et al., 2004; Barron et al., 2010).

Modeling groundwater became a helpful tool for management issues of water resources using several codes such as V-MODFLOW (Abualtayef et al., 2017), PTC model (Goumas et al., 2017) and FEFLOW (Gad and Khalaf, 2015; Du et al., 2016) for current management evaluation and irrigation planning suggestions.

In this paper a numerical model was established as a management tool for the regional shallow aquifer of Sfax. Since this region is characterized by an arid climate, a high population and an agricultural consumption, the following model takes into account the recharge variation caused by climate change and the increasing pumping rates all over the region to simulate the water table behavior for a better management and control of water resources.

2. Study area

Sfax is one of the biggest coastal cities in Tunisia. It is located in the eastern part (Fig. 1). Its population is estimated by 955.421 inhabitants with a growth rate of 1.11%. The high demography is related to a developed agricultural activity, since the region is classified on the national scale as the first agricultural producer with 40% of Tunisia's olive oil and 30% of almonds. The climate in this area is arid to semi-arid with irregular and torrential precipitations. These are characterized by their variability in time and space with an average of 223.6 mm/year over the period 1980–2013. The annual average temperatures recorded for the same period is about 19.5 °C with a variation between a maximum of 20.5 °C recorded in 1999 and a minimum of 18.1 °C corresponding to 1980 (Fig. 2). It has an increasing linear trend along that period showing a light warming. The study area has a monotonous and mostly plane topography provided with some reliefs, some "sebkhas".

Sfax region has a developed stream network where major wadies have temporary activity related to the rainfall. The soil nature is dominated by a sandy and sandy clay lithology. The aquifer is mainly of Miocene, Pliocene, and Quaternary. The transmissivity values of the phreatic aquifer are ranging between 10^{-6} m^2/s and 1.5 10^{-2} m^2/s (DGRE, 2005).

The rainfall infiltration mainly causes the recharge. There are also some other factors helping the recharge such as the water irrigation and the domestic sewage on the urban side. The water table flows from the Northwest to the Southeast towards the Mediterranean Sea.

Piezometric map shows that the curves values are about 150 m in Regueb region and get negative in some coastal regions such as Djbeniana (Fig. 3).

3. The modeling approach

Tabular and shapefile data base was integrated and treated in ArcGIS 9.3, which is a common tool for geological studies (Rejani et al., 2008; Hadded et al., 2013; Xu et al., 2011; Khadri and Pande, 2016). The Data base is collected and treated in GIS tool: ArcGIS, since it allows an easy access with the ability to develop, update and modify data. The geographical data base that was processed and sorted by ArcGIS was actually the input to GMS and consequently created the MODFLOW numerical model (Gogu et al., 2001). Thus, it is possible to calibrate and validate the hydro-dynamical model but also to consider the aquifer system behavior.

In this paper, MODFLOW 2000 code was used through GMS 6.5,

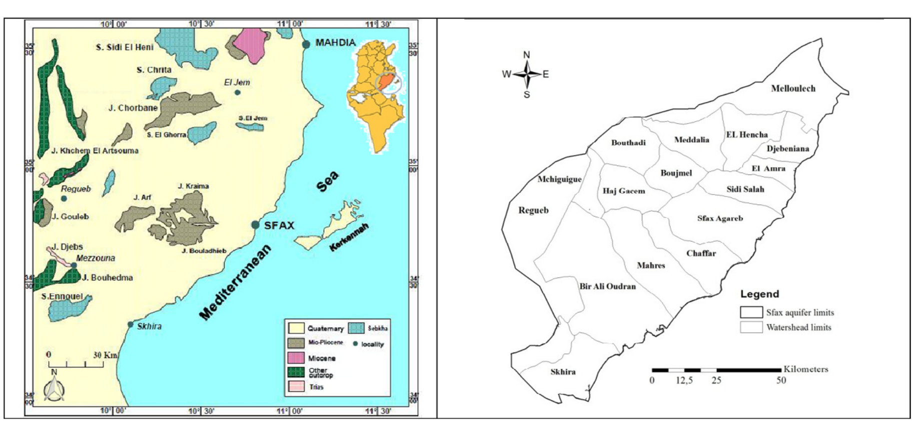

Fig. 1. Location of the study area.

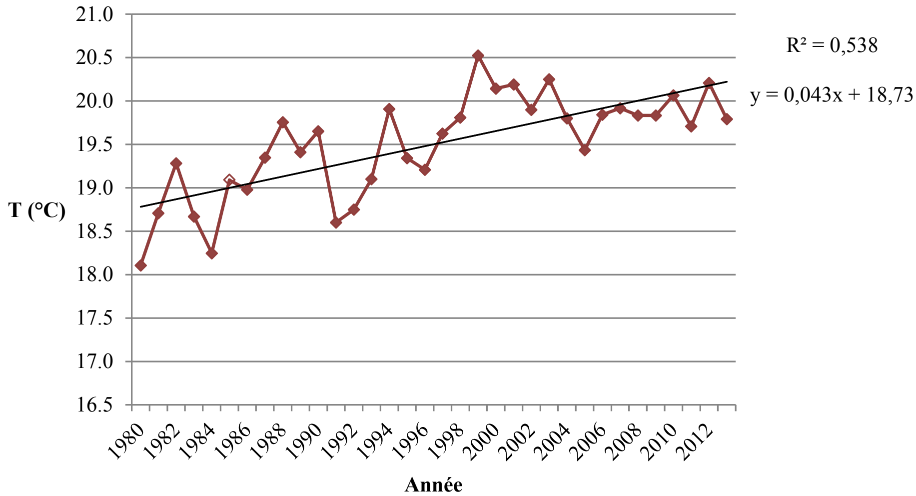

Fig. 2. Variation of annual average temperature in Sfax for 1980–2013 (source INM-Sfax).

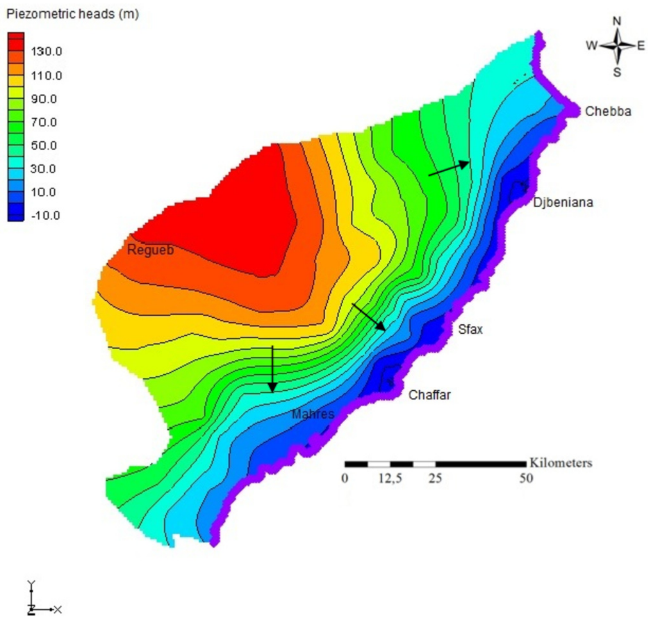

Fig. 3. Piezometric map for 2013.

since it supports many types of numerical codes and provides a complete interface for MODFLOW. This was done in order to create the numerical model of the aquifer and forecast the groundwater level under climate change and consumption scenarios. In fact, GMS offers the possibility of using ArcGIS files, therefore, both softwares were coupled to develop the MODFLOW model using the conceptual model approach.

MODFLOW(Harbaugh et al., 2000) is so far one of the most common numerical models used for groundwater evaluation under climate change and consumption variation (Jilali, 2009; Gaur et al., 2011; Zghibi et al., 2011; Lachaal et al., 2012; Bougheriou et al., 2014). The software popularity is due to its simple instructions (Barron et al., 2010; Gaur et al., 2011), the ability to develop new modules (Schmitz et al., 2009) and to check errors in addition to the open access to its source code (Winston, 1999). MODFLOW is based, actually, on the finite difference model to study the different types of aquifers regardless of their nature and properties using the following governing equation (1).

$$\partial/\partial x \; Kx \; \partial h/\partial x + \partial/\partial y \; Ky \; \partial h/\partial y + \partial/\partial z \; Kz \; \partial h/\partial z = Ss \; \partial h/\partial t \quad (1)$$

Where

Kx, Ky, Kz: hydraulic conductivity
h: potentiometric head
S: specific storage
t: time

It is able to design the aquifer in its steady and transient state, to represent its boundary conditions and its various interactions (charging, discharging, pumping and drainage) (Kim et al., 2008), while respecting the regional nature such as arid, semi-arid and tropical study areas (Yang et al., 2011).

As a first step, the boundary conditions are imposed by the limits of the field in order to provide a possible solution of a physical problem, such as liquid flow (Banton and Bangoy, 1997). Since Sfax shallow groundwater was the subject of several studies and projects to define the geometry of the aquifer system and to understand its hydrodynamic (Smida, 2008; Trabelsi, 2008; Saidi, 2011; Triki, 2012). Therefore, these studies were taken into consideration in addition to adjacent aquifers information (Smida, 2008; Saidi, 2011) in order to know the geological boundaries of the aquifer system to the North (compared with the system of Mahdia) and West (compared with the system of SidiBouzid). As matter of fact, the shallow groundwater of Sfax was seen as a set of two aquifers for long time: an interior aquifer and a coastal one. Hence, the INC project (2003) made a numerical model of two independent aquifers behavior. But, in 2006, it was confirmed as a single aquifer (Brahim, 2006). The limits of Sfax groundwater system does not correspond to the administrative boundaries region. Indeed, there is unanimity in researches and in CRDA-Sfax reports for the limit on the west side coinciding with the "Bled Regueb" region. Thus, a part of the SidiBouzid governorate was included in the study area (Smida, 2008; Trabelsi, 2008). The northeast limit is therefore defined by reference to the Trabelsi (2008) and Saidi (2011) labors which have demonstrated the continuity of Sfax aquifer with "KsourEssaf" area. The conceptual model is then determined based on the aquifer geological boundaries and boundary conditions are introduced to MODFLOW. According to the aquifer geometry, no flow boundary condition was applied to its border (North, West and South). Meanwhile, the constant head was applied to its coastal limit. The imposed flow rates were attributed

to wells for pumping and to all the active cells for recharge. The shallow aquifer system covers several basins with an average depth of 70 m within the sandy and sandy-clay deposits of the Plio-Quaternary. Respecting these boundaries, the aquifer is independent and according to the structural structures, it is not influenced by tectonic event.

The choice of cells width depends on data base availability and calculation accuracy in each one (Romanazzi et al., 2015). In this paper, the study area was discredited into 15522 active square cells (250×250 m), while those located outside the boundaries are inactive. The economic and cultural growth in the region is reflected on consumption rates. For an existent resource volume 39.12 Mm^3, the extraction is about à 53.65 Mm^3 in 2013 (CRDA, 2014). This increasing tendency started 15 years ago with a high rate of wells creation and it is more pronounced in coastal basins that are experiencing a water deficit that varies from one basin to another (in 2013, 5.95 Mm^3 in Djbeniana, Skhira with 4.29 Mm^3, Hencha with 3.03 Mm^3, Chaffar 2.89 Mm^3, and Sfax-Agareb with 2.56 Mm^3). The quantitative evolution in abstraction of water resources presents a logarithmic trend with a regression coefficient R^2 of about 0.85.

The piezometry of the Sfax shallow system for the year 2013 shows a general flow from the North-West to the Mediterranean Sea. The water table level is negative at the coast and it reaches 150 m at Regueb zone. Comparing the situations of the years 2003, 2008 and 2013 the aquifer has the same direction of flow; nevertheless, some variations are noted between these three states. There is a decrease in the piezometry level of the water table in the coastal zones as a result of the excessive exploitation especially in the zone of Chaffar and Djbeniana. Therefore, the difference from one map to another is downstream where the hydraulic gradient becomes stronger relatively to increasing exploitation.

4. Results and discussion

The data used in MODFLOW consist of (1) the aquifer system stress factors, (2) the aquifer system and strata geometry, (3) the hydrogeological parameters of the simulated process and (4) the main measured variables (Xu et al., 2011). Thus, layer information is attributed to cells.

The model is reduced to only one layer to simplify numerical calculations, where the top is defined from DEM since the aquifer system is shallow and unconfined (Fig. 4). The altitude is ranging from sea level to 250 m. To determine the aquifer bottom, boreholes data are used after a validation of their location and altitude by checking them with used DEM to make sure that the system input are correct. The depth of the bottom is detected in each well according to its lithological nature and converted to an altitude and then the whole layer (Fig. 5) is obtained after statistical interpolation. The study area has three types of hydraulic conductivity which are high, moderate and low. They vary according to lithology classes and from a basin to another. The hydraulic conductivity values are obtained from pumping tests of 56 boreholes and it is defined for all the active cells (Fig. 6).

The steady state was performed for the year 2003, since piezometry data are available and have an acceptable repartition in the study area. These values are used as starting heads.

For this simulation, the total exploitation of Sfax aquifer system for 2003 is about 34.76 Mm3, while the number of wells is equal to 11585 (Fig. 7) (CRDA-Sfax, 2009). Therefore, as an input it is necessary to insert the extraction rates for this year by dividing it on the number of wells in each point representing a surface well so that inserted rates are similar in the same basin but different from one basin to another as presented in Table 1.

Unlike paleo-groundwater, the recharge of shallow water tables is renewed. For this reason geochemical and isotopic methods could be used to identify the process of recharge (Hamed et al., 2013, 2014; Mokadem et al., 2016; Ayadi et al., 2017; Hamad et al., 2017) but mostly, the quantitative aspect is taken into consideration in order to create of a numerical model.

To calculate recharge rates several methods were adopted such as the Estimation of Recharge in Overexploited Aquifers (Estimación de la Recarga en Acuíferos Sobreexplotados) (Murillo and Roncero, 2005) and chloride mass balance (Schoeller, 1960; Schmidt et al., 2013). For the arid and semi-arid regions of southern Tunisia, recharge calculation are particularly obtained by attributing a percentage going from 2 to 6 to precipitation values

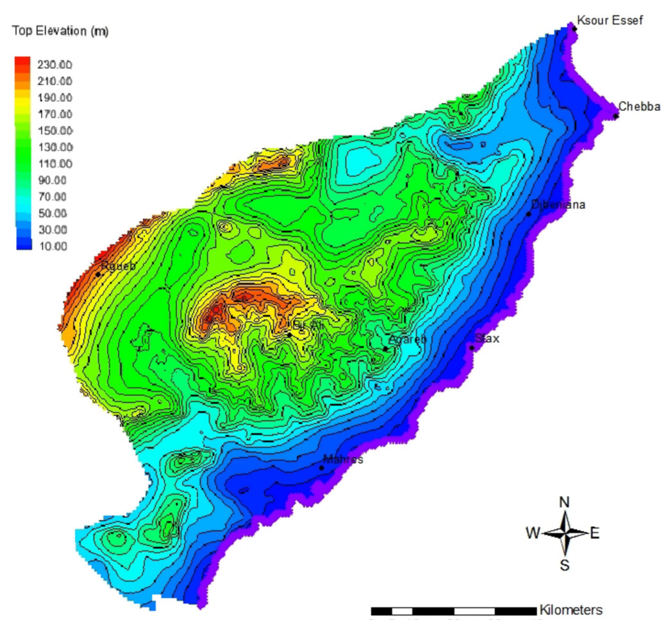

Fig. 4. Aquifer top map.

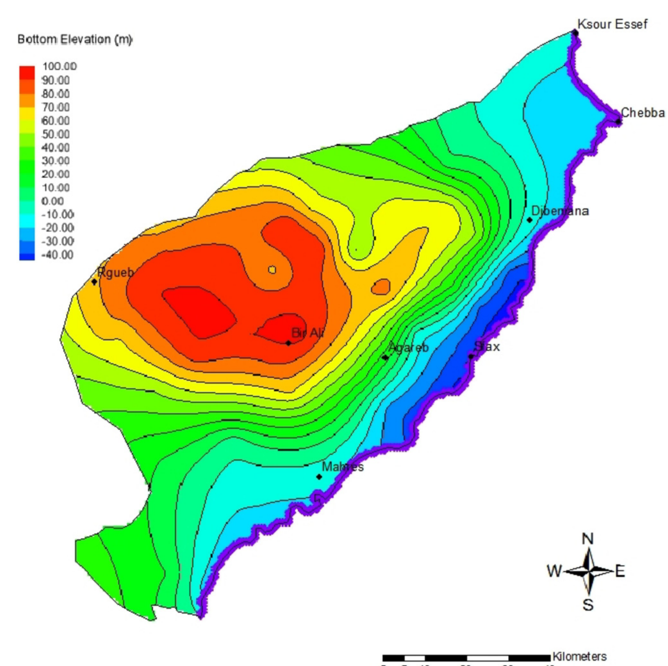

Fig. 5. Aquifer bottom map.

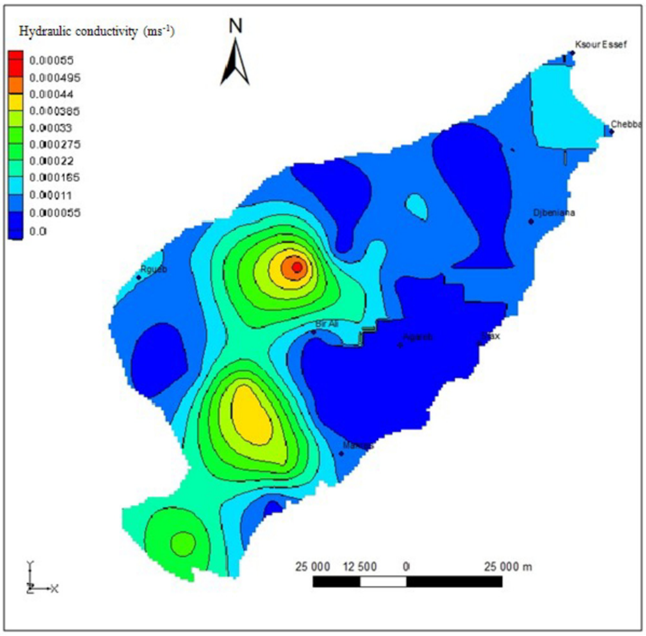

Fig. 6. Hydraulic conductivity map.

according to the lithology classes or by affecting Fersi equations to outcrop map. These equations are the most used in Sfax since they take into consideration the climatic and lithological characteristics of the study area (Fersi, 1979). After a comparison between these different methods the last one was the most efficient and had the most suitable results suitable. However, this method couldn't be applied to the numerical model because of the great number of outcrop polygons that affects the model runs calculations.

Therefore, a potential recharge map was created using a

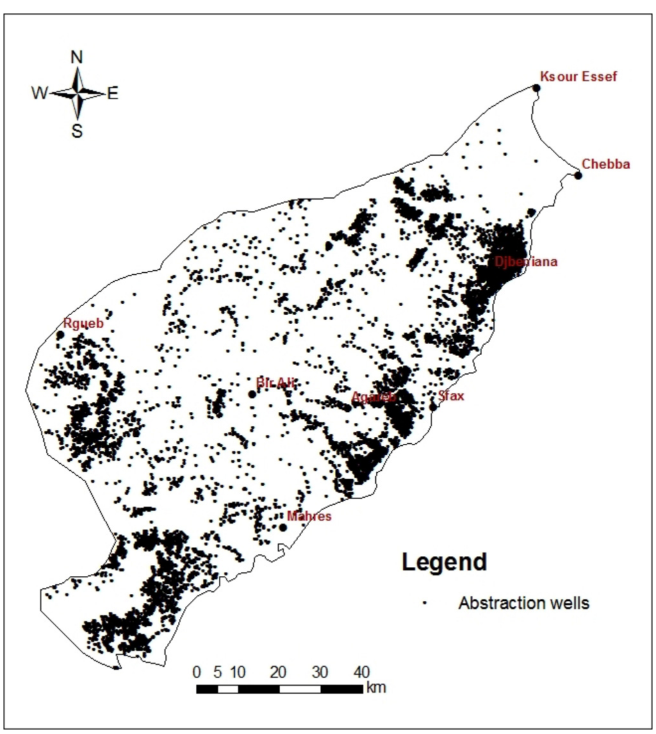

Fig. 7. Abstraction wells location map.

Table 1
Extraction rate values in Sfax region for 2003 (CRDA, 2009).

Basin	Wells Number	Extraction rate per basin (Mm^3/year)	Extraction rate per well 10^{-5} m^3/s
Hencha	927	2,92	12,45
Amra	879	1,66	7,14
Sidi Saleh	473	0,89	6715
Djebeniana	2654	7,17	11,24
Mahres	277	0,91	11,62
Chaffar	1286	2,85	8,18
Skhira	1555	6,31	13,90
Meddalia	423	1,37	13,19
Sfax Agareb	1627	6,33	14,88
Boujmel	152	0,35	;,,, 9,64
Haj Gacem	68	0,3	15,84
Mchiguigue	46	0,1	8,12
Bir Ali Oudran	1428	3,29	8,38
Bouthadi	108	0,31	12,12
Melloulech	586	4,28	28,08
Regueb	751	3,6	17,36

multicreteria evaluation (MCE) by ArcGIS 9.3. In fact the new recharge map is a result of the integration of different parameters as thematic maps to the GIS model which are the slope, topography, stream network and lithology (Sikdar et al., 2004; Abdalla, 2012; Bougharlou et al., 2015). These maps were classified into three classes by assigning the most favorable class for the highest contribution. Then, each one has been given a weight value. The potential recharge zones map is established using the raster calculator function on ArcGIS model after weights attribution to the classified maps. The resulting map is obtained using the: equation (2) :

$$\text{Calculated map} = 2\text{x slope map} + 3 \text{ x topography maps} + 3 \text{ x stream network maps} + 2 \text{ x lithology maps} \quad (2)$$

The polygons number is reduced to 432 instead of 3420. The recharge value is calculated for the polygons by applying Fersi equations (3) and (4) and using meteorological values from "El Maou" Station:

$$I1 = [(5/100) *P] - 3.4 \quad (3)$$

$$I2 = [(2.5/100) *P] - 4.6 \quad (4)$$

Where I1 is the efficient infiltration for moderate permeability (mm), I2 is the efficient infiltration for low permeability, and P is the average of annual precipitations (mm/year).

Once the model is executed, the first step was checking the aquifer geometry data especially the bottom level. Then, it is necessary to calibrate the model and adjust the values of the hydrodynamic parameters in order to obtain a calculated piezometry that conforms to the measured one. Actually, these parameters were calibrated through an iterative process (Xu et al., 2011) because they were relatively uncertain in the study area and did not present an excellent geographic distribution. However, the adjusted values could comply with the field and literature data (Chaaban, 2011). Several runs were made for the steady state in order to obtain a suitable fit with the observed obtained between computed and observed values of piezometry after an adjustment of the hydraulic conductivity which is the parameter that was calibrated because of the varied nature of soil and logs. The calculated map shows some similarity to the measured one with a slight difference upstream the study area where data is rare (Fig. 8).

The transient state is a major step to set the model. It is used essentially to validate the steady state and to follow the evolution of

the groundwater (Boughariou et al., 2014). The boundary conditions are kept the same as the steady state simulation. The calibration was performed for the period from 2004 to 2013 that was divided into ten stress periods for which recharge and extraction data is required.

As regards consumption, only the annual variation of basin extracted water is available. Unlike 2003, the location of the wells is not updated and new created wells could not be placed on the map. Thus, it is necessary to divide the annual total consumption for each basin by the number of wells located on the map instead of the actual number of existent wells per basin. For the transient state, as in the steady state, Fersi equations are applied to potential recharge zones by varying the values of the average annual rainfall from “El Maou” station for every year. Thus, the recharge for the period 2004–2013 was inserted in 432 polygons considering their infiltration quality. Another parameter is required for the transient state which is the specific yield (Fig. 9) and because of the lack of data. The values which vary between 10 and 40% are used from the literature (Johnson, 1967; Castany, 1982; Banton and Bangoy, 1997; Smida, 2008; Saidi, 2011). The model validation was made for the stress periods 2008 and 2013 through 25 wells. This model was calibrated by the scatter diagram where observed values are compared to the calculated ones, and the root mean squared of residual errors. For 2008, the simulated map was consistent with the original one with a good correlation between simulated and calculated values ($R^2 = 0.9$) in the scatter diagram (Fig. 10). For 2013, the calculated map also shows a coherent pattern with the observed one, since the simulated heads have a correlation coefficient $R^2 = 0.9$ in the scatter diagram compared to the measured heads (Fig. 11). The values of the RMSE for the steady state were about 12.5 while they were about 5.7 and 5.8 for 2008 and 2013. RMSE decreased by 54% showing an enhancement compared to the steady state even though they appear to be relatively high because

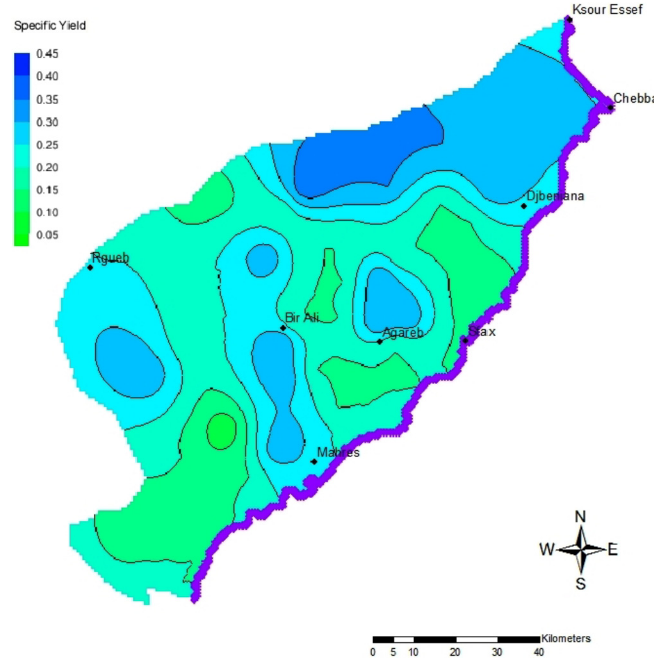

Fig. 9. Specific yield map.

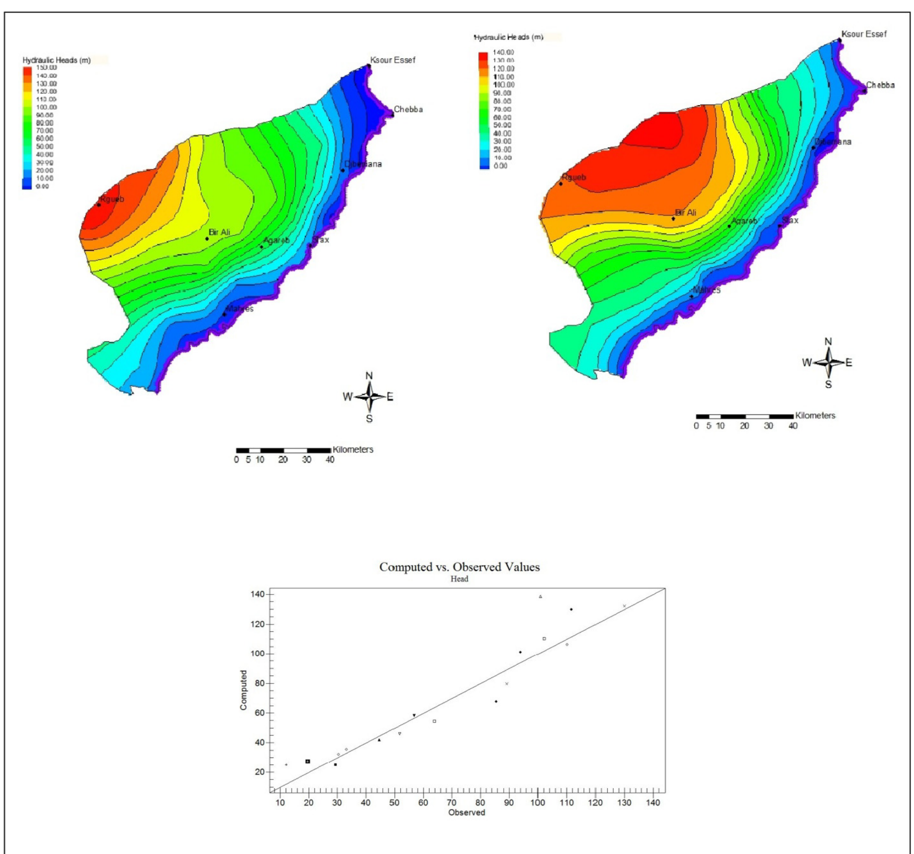

Fig. 8. Steady state (2003): A) Mesuread map; B) calculated map; C) Scatter diagram.

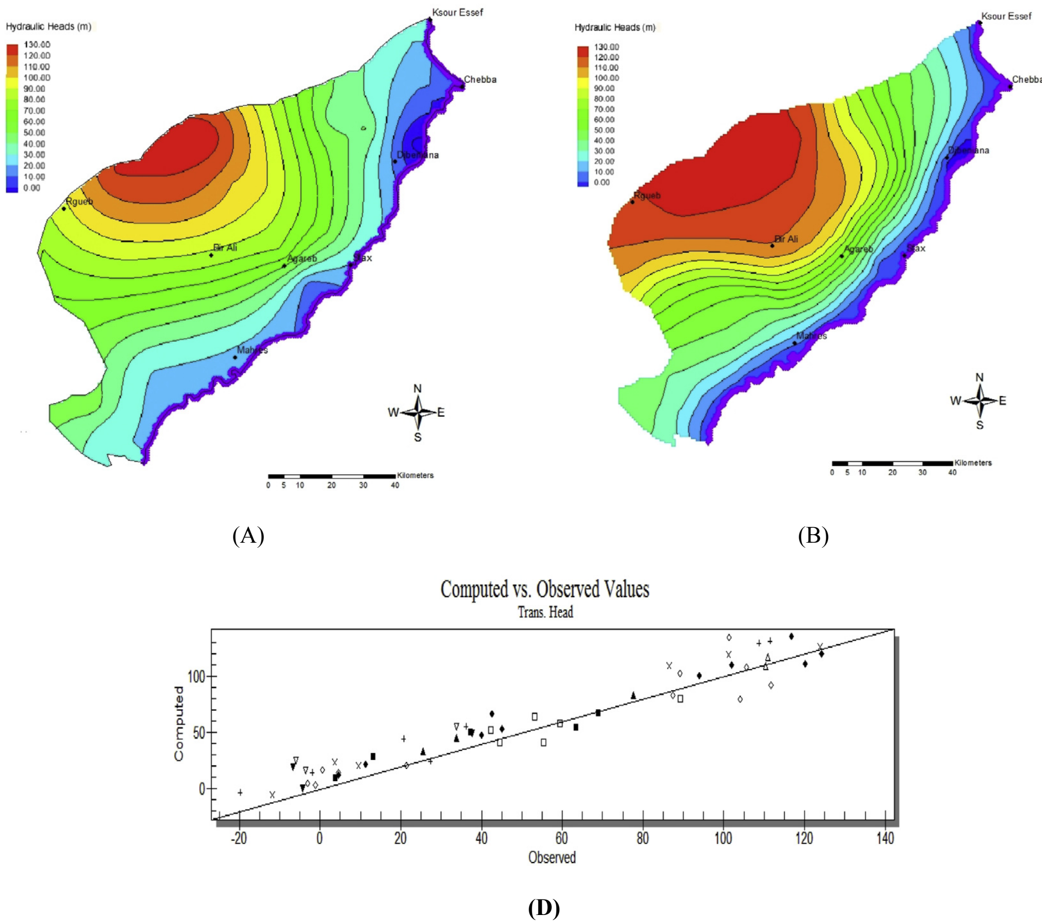

Fig. 10. Transient state (2008): A) Mesuread map; B) calculated map; C) Scatter diagram.

of the lack of data on Regueb region. According to Abderrahman and Rasheeduddin (2001) the important results are not only the calculated piezometry but also the variations in heads caused by stresses in the aquifer system as long as the model simulates water table variation patterns correctly.

Because of the complexity of rainfall patterns, the climate models are necessary for the prediction of precipitations. To estimate the amount of rainfall in Sfax in 2020 and 2050, the climate scenario was adopted from the National Strategy for adaptation of Tunisian agriculture and ecosystems to climate change that was developed as part of collaboration between the Ministry of agriculture and water resources (MARH) and the German international cooperation agency (GIZ). Actually, according to this strategy, the climate projections were calculated by the numerical general circulation model HadCM3 (Hadley Centre Coupled Model version 3), which is a coupled atmosphere-ocean that has been developed by the Hadley Centre in England. It was selected among the models: Canadian (CGCM2), Australian (CSIROmk2) and American (DOEPCM). Ultimately, HadCM3 was used for the A2 and B2 scenarios for projected climate in 2020 and 2050 with reference to the period (1961–1990). The HadCM3 expected an increase of the annual average temperature in Tunisia by 1.1 °C in 2020 and 2.1 °C in 2050 accompanied by a general decrease in rainfall. For Sfax region, the numerical model provides a temperature increase of 0.8 °C by 2020 and 1.6 °C by 2050 with a decrease in rainfall of 6% and 15% by 2020 and 2050, respectively. These variations once attributed to the average temperature and precipitation of the period 1980–2013, we would have 20.3 °C and 210 mm, respectively, by 2020 while it would be 21.1 °C and 178.5 mm in 2050. These values are used in both scenarios with a variation of groundwater abstraction.

For the first scenarios, the consumption for 2020 and 2050 is maintained equal to that of 2013, to determine the evolution of the water table in the case of its protection instead of following its increasing extraction trend. This scenario aims actually to determine the effect of climate change manifested as a decrease in annual precipitation and therefore the recharge rates without increasing the exploitation rate.

Hartmann et al. (2014) also forecast a decreases of recharge as a result of decreases of precipitation a Mediterranean Karst aquifers by using a process-based simulation model VarKarst. In fact, Studying recharge is an important step before modeling groundwater behavior. Hartmann et al. (2015) have simulated recharge from 2002 to 2012 in several Mediterranean krast landscapes. They showed that recharge rates are sensitive to subannual climate variability and that large-scale modeling approaches tend to underestimate recharge volumes after a comparison of their results with recharge observations across the Europe and the Mediterranean.

However, for the second scenario, the groundwater abstraction by the year 2020 was estimated from the trend curves of each watershed by the use of the equation corresponding to the logarithmic trend line. The total consumption for 2020 would be 61 $Mm^3$and would increase to 61.06 Mm^3 by 2050 according to the current tendency. We notice that the consumption in 2020 is far

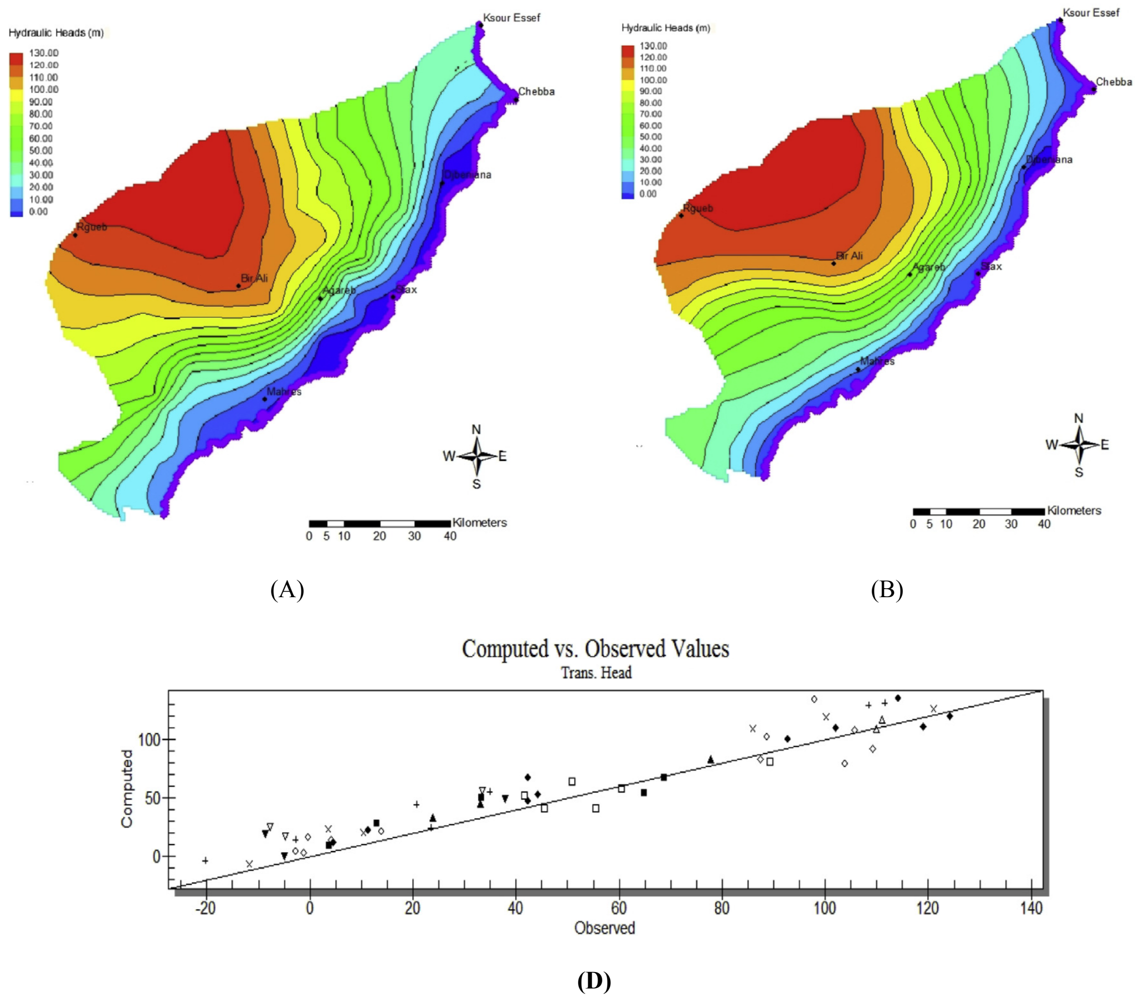

Fig. 11. Transient state (2013): A) Mesuread map; B) calculated map; C) Scatter diagram.

different than in 2013 for all watersheds; however, it is almost constant between 2020 and 2050 for their majority.

The Simulated map for the first scenario by 2020 (Fig. 12) generally shows a similar shape to that of the calibrated map of 2013. On the other side, some differences are observed when comparing the two maps by calculating drawdown map. The general drawdown is about 0.5 m across the study area except for "Djbeniana" region where it reaches approximately a maximum of 4 m. The calculated map for 2050, using this scenario, presents a highlighted difference in "Djbeniana" area where dry cells appear. In addition, the "Naoual" area shows a withdraw of heads curves that could be explained by the high consumption in the "Skhira" region. The value of the general drawdown is higher than 2020 and reaches 1 m. It increases in the "Chaffar" region and around the dry area of "Djbeniana".

In spite of recharge, Stigter et al. (2014) took into consideration, the consumption and the sea level variation in their study of climate change impact on groundwater resources in three Mediterranean areas. They have calculated the aquifer recharge and developed the groundwater flow models based on "A1b climate scenarios" for two periods: 2020–2050 and 2069–2099. The groundwater levels are predicted to decrease. They responded more to the expected recharge diminution and increasing exploitation while they showed negligible variation because of sea level rise.

In the second scenario for 2020 (Fig. 13), where consumption is growing, the overall decrease in groundwater level is about 1 m. The calculated map, compared to the one simulated for constant consumption for the same year, shows a higher stress with the appearance of a dry zone in the "Djbeniana" region and a shift of the water level curves to "Sabkhet Naoual". This hydraulic head state is intermediate to the two situations provided for constant extraction. The stress situation worsens for increasing consumption scenario in 2050. Indeed, the drawdown is increasing in southwest areas and "Djbeniana" region, having a dry area more developed and reached its maximum (structure problem).

These results are comparable to the findings in other studies. The Global Circulation Models (GCM) HadCM3, used for the climatic scenarios in this study was also used by Jackson et al. (2011). In fact HadCM3 was one of the 13 GCMs running under the (A2) emissions scenario to simulate the behavior of Chalk aquifer in Central-southern England. They predict a 4.9% reduction in annual potential groundwater recharge by the 2080s and a decrease of groundwater levels and river flows, with ten predicting a decrease and three predicting an increase. These predictions are in full agreement with the results of other climate change models: Piras et al. (2014) studied the impact of climate change on water resources in an Italian basin. They applied four combinations of global and regional climate models on a numerical model. For a decrease of 12.7% in average rainfall in the future (2041–2070), they predict

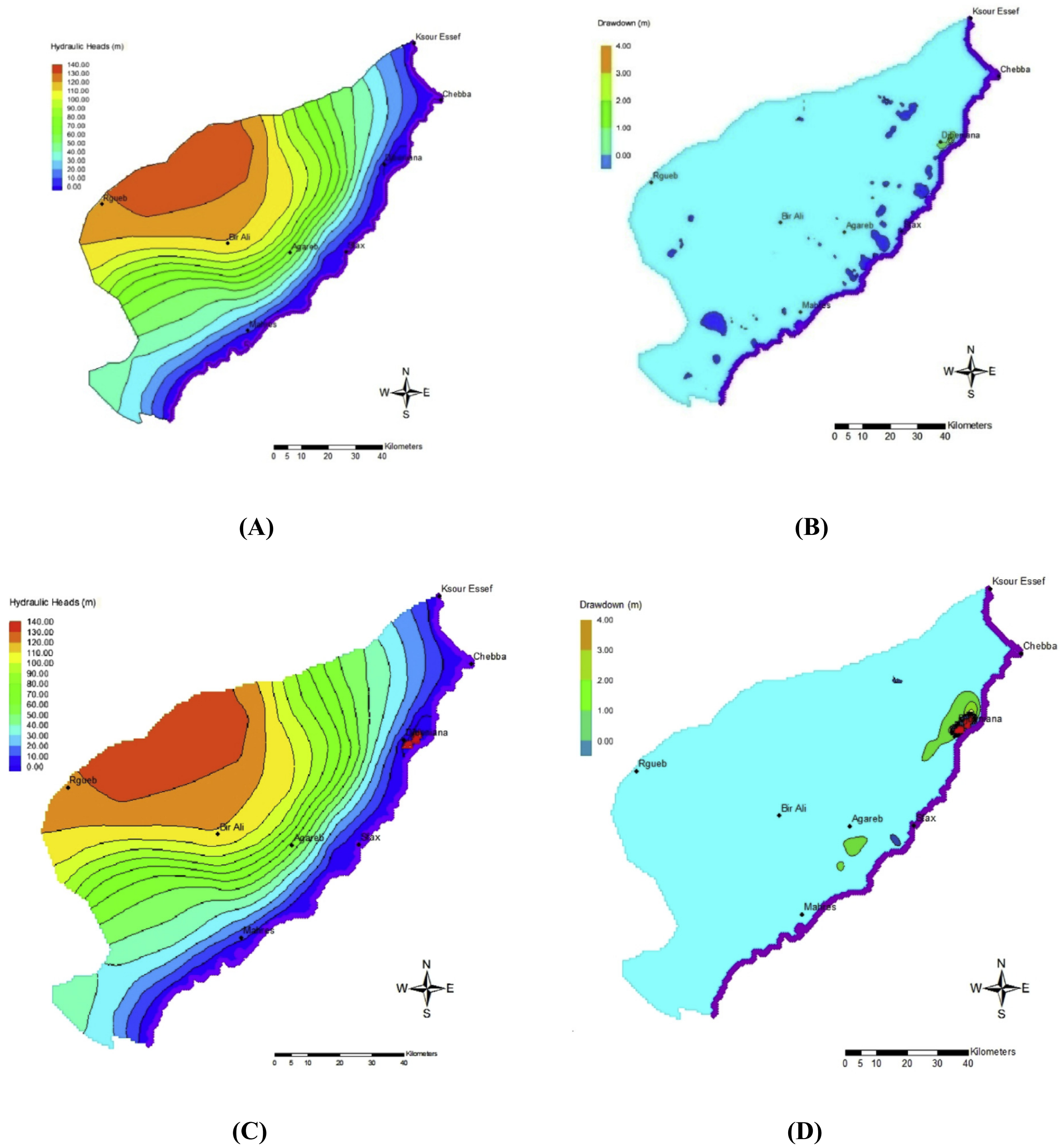

Fig. 12. Simulation under a constant consumption: A) Calculated map for 2020; B) Drawdown map between 2013 and 2020; C) Calculated map for 2050; D) Drawdown map between 2020 and 2050.

a diminution in annual runoff and in the groundwater level.

Caballero and Ladouche (2015) used an inverse modeling method based on wavelet analysis on only two piezometers of a Mediterranean confined coastal aquifers. The simulation took under consideration pumping variation and five scenarios of climate change. As a result it highlighted a decrease in the piezometric level of the water table (50 cm) that would get significant by 2050 and projected a seawater intrusion related to the rise in the sea level. Lemieux et al. (2015) used FEFLOW numerical model to study the climate change effect by 2040 on the groundwater resources of the Magdalen Islands. This study took into consideration more variables such as sea-level rise, groundwater recharge decrease and coastal erosion. These variables would cause a migration of saltwater/freshwater interface inland over a distance of 37 m and to vertically increase near the coast to 3.1 m further inland. Romanazzi et al. (2015) studied a karstic aquifer in southern Italy that is threatened by overexploitation, climate change and seawater intrusion. They used MODFLOW and SEAWAT numerical models and simulated water table level and salinity variations under three past scenarios (from 1930 to 1999) and three future scenarios that consider climate change by 2060. As a result, they confirmed the decrease of water table level for the past period and expect a dramatic drop in the future.

5. Conclusion

Sfax's demographic and economic characteristics make it one of the most water consuming regions exhausting water resources. The

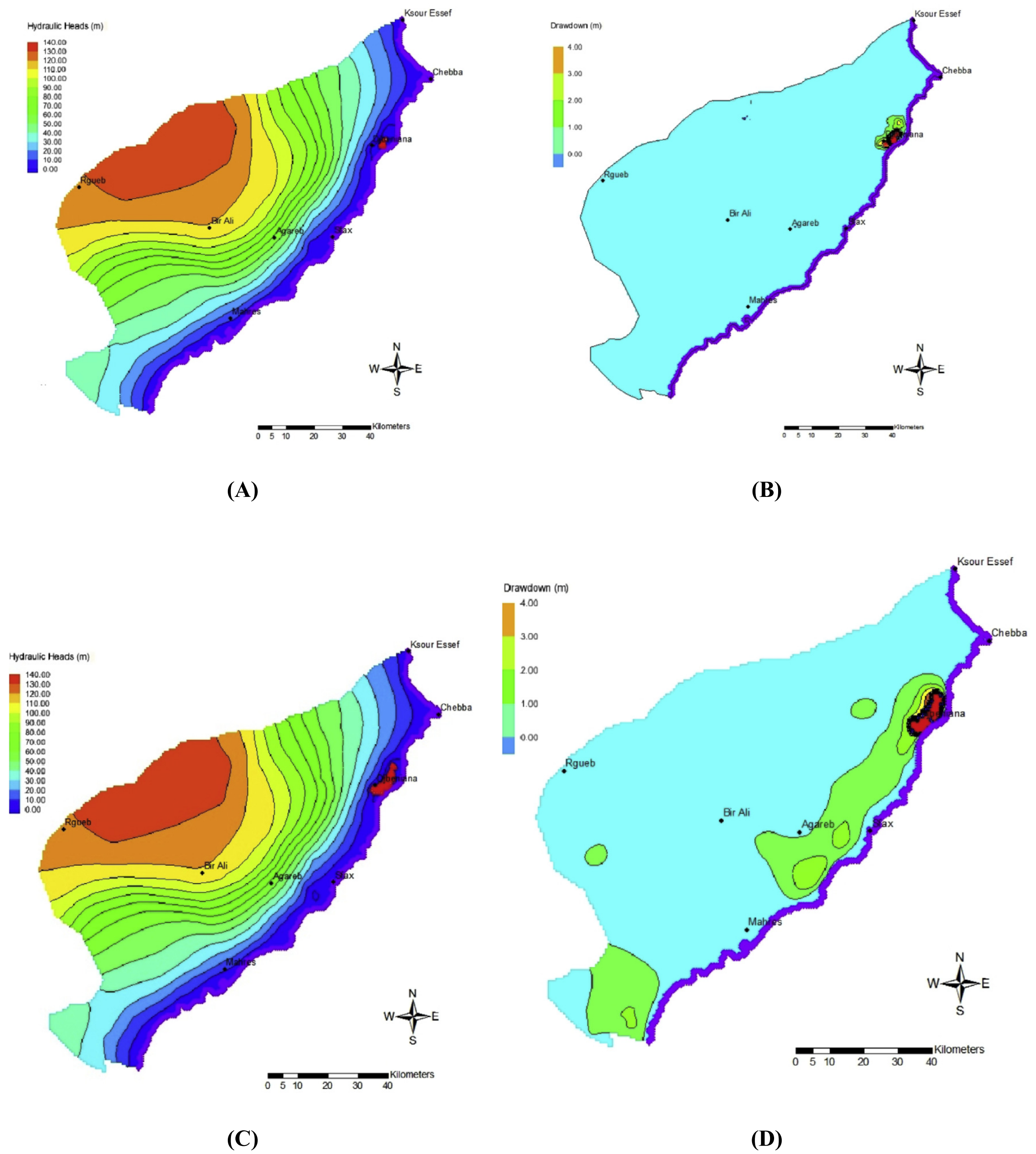

Fig. 13. Simulation under an increasing consumption: A) Calculated map for 2020; B) Drawdown map between 2013 and 2020; C) Calculated map for 2050; D) Drawdown map between 2020 and 2050.

excessive exploitation of water resources is not the only reason. Indeed, the semi-arid to arid climate acts negatively and causes a lack of precipitation. This factor is further impacted by global warming. In this paper, a numerical model was established using MODFLOW to forecast the level of the shallow groundwater of Sfax under climate change and the different values of consumption. The numerical model is established in a steady state (2003) and transient one (2008 and 2013). The calibration correlates well with the actual situation although it shows some anomalies up stream and in southwestern zone where data is lacking. In the climate scenario a rainfall decrease by 6% and 15% in 2020 and 2050, respectively, was adopted; first applied to a constant consumption that is equal to that of 2013, then to increasing values according to the tendency curves. The MODFLOW simulated heads show a general drawdown of the aquifer level for all the scenarios that is about 0.5 m in 2020 for a low consumption and that would be worse by 2050 especially under a growing exploitation. The two coastal zones that are more threatened by global warming and excessive extraction are “Djbeniana” and “Chaffar”. In these zones, the drawdown is higher than the rest of the region. Given the alarming situation of the aquifer, we recommend further management of the watersheds using two main strategies; first, carrying out water and soil conservation structure in order to compensate the anarchistic consumption and second, increasing the groundwater recharge and reducing seawater intrusion in the region. This could improve the worsened situation especially at “Djbeniana” watershed. Besides, various human activities must be controlled to minimize the water degradation.

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